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FINAL REPORT

"The Development of a Plan for the Assessment, Improvement and Deployment of a Radar Acoustic Sounding System (RASS) for Wake Vortex Detection"

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1. Abstract

This report describes the activities completed under a grant from the NASA Langley Research Center to develop a plan for the assessment, improvement, and deployment of a Radar Acoustic Sounding System (RASS) for the detection of wake vortices. A brief review is provided of existing alternative instruments for wake vortex detection. This is followed by a review of previous implementations and assessment of a RASS. As a result of this review, it is concluded that the basic features of a RASS have several advantages over other commonly used wake vortex detection and measurement systems. Most important of these features are the good fidelity of the measurements and the potential for all weather operation. To realize the full potential of this remote sensing instrument, a plan for the development of a RASS designed specifically for wake vortex detection and measurement has been prepared. To keep costs to a minimum, this program would start with the development an inexpensive laboratory-scale version of a RASS system. The new instrument would be developed in several stages, each allowing for a critical assessment of the instrument's potential and limitations. The instrument, in its initial stages of development, would be tested in a controlled laboratory environment. A jet vortex simulator, a prototype version of which has already been fabricated, would be interrogated by the RASS system. The details of the laboratory vortex would be measured using a Particle Image Velocimetry (PIV) system. In the early development stages, the scattered radar signal would be digitized and the signal post-processed to determine how extensively and accurately the RASS could measure properties of the wake vortex. If the initial tests prove to be successful, a real-time, digital signal processing system would be developed as a component of the RASS system. At each stage of the instrument development and testing, the implications of the scaling required for a full-scale instrument would be considered. It is concluded that a RASS system, developed for the specific application of wake vortex detection, could become part of a robust Aircraft Vortex Spacing System (AVOSS). This system, in turn, could contribute to Reduced Spacing Operations (RSO) in US airports and improvements in Terminal Area productivity (TAP).

2. Introduction

The capacity of airports is constrained severely by the air traffic control (ATC) system's consideration for potential wake vortex encounters. The present Instrument Flying Rules (IFR) restrictions are based on aircraft weight. The "3-4-5-6 rule" sets the separation of distances between aircraft by categories from small (less than 41,000 lbs) to heavy (greater than 255,000 lbs). These separations are viewed as very conservative (see Ref. 1): however, since there remains sufficient uncertainty about the wake vortex behavior under different atmospheric conditions, there are significant technological barriers to improvements in Terminal Area Productivity (TAP). NASA administers the TAP program. Donohue and Rutishauser (Ref. 2) provide an overview of the effect of aircraft spacing on air transportation capacity. The economic impacts of even relatively minor increases in TAP are considerable. For example, Lee et al. (Ref. 3) estimate that the savings at Boston Logan International (BOS) Airport would be at least \$92 million (1993 \$) for the least aggressive of the TAP increments considered. This would involve Reduced Spacing Operations (RSO) including an Aircraft Vortex Spacing System (AVOSS) with wake vortex sensors. NASA Langley Research Center is developing an AVOSS as part of the RSO sub-element of the TAP program. Hinton (Ref. 4), Perry et al. (Ref. 5), and Hinton et al. (Ref. 6) describe the evolution and status of this program. The RSO activity aims to develop technologies to reduce lateral and longitudinal spacing in non-visual conditions. This includes the AVOSS as well as Airborne Information for Lateral Spacing (AILS) components.

The basic AVOSS architecture includes: a meteorological subsystem to describe the vertical profiles of wind, turbulence and temperature; a prediction subsystem that uses the weather profile and descriptions of the aircraft fleet to predict wake behavior for each aircraft type; and a wake vortex sensor to verify that the wakes are behaving within the range of predicted values. There are several sensors that have been considered. These include ground-mounted wind line anemometers; ground based Doppler radar; continuous wave (CW) and pulsed LIDAR (Light Detection and Ranging); a Monostatic Acoustic Vortex Sensing System (MAVSS); SOCRATES (Sensor for Optically Characterizing Remote Atmospheric Turbulence Emanating Sound); a large microphone beam-forming array; and a RASS (Radio/Radar Acoustic Sounding System). The wind line, also known as the Ground Wind

Vortex Sensing System (GWVSS), has produced the bulk of the currently available data on wake vortex transport in the airport environment. It relies on the detection of the wake vortices as they descend towards the ground. As such it is not a remote sensing system and cannot determine with certainty if vortices are present in the flight path regions. Radar systems, both X- and C-bands have proved inconclusive as the radar cross section of a wake vortex is very small and contamination from ground clutter is a problem at low angles. LIDAR systems have proved to be an effective method for wake vortex detection. They have high spatial and velocity resolution. However, they are not all-weather instruments and their range is limited. The MAVSS (see Ref. 7) relies on the Doppler shift in the incoherent acoustic backscatter from turbulence convected within the wake vortex to measure the vortex velocity. It provides moderate resolution of the wake vortex profiles out to 500 m. The SOCRATES system proposes to use a laser microphone to measure the sound emitted by wake vortices from a considerable distance. However, whatever the merits of the optical microphone, it is not known whether wake vortices generate a detectable acoustic signature. In fact, given the relatively low velocities in the wake vortex, the signature is likely to be very low frequency, very low in intensity, and thus extremely difficult to separate from the ambient airport noise environment. Some of the potential signal to noise ratio problems with SOCRATES can be overcome with the use of an acoustic microphone array. Dougherty et al. (Ref. 8) successfully deployed a large microphone beam-forming array. The instrument was able to resolve the wake vortices and measure their separation, height and sinking rate. Though this system appears promising it has yet to be tested in a harsher acoustic environment and in more inclement weather than that encountered outside the Denver Airport during the referenced experiments. The RASS is described in some more detail below.

The RASS relies on acoustic stimulation to enhance the radar return using the Bragg effect. North and Peterson (Ref. 9) first reported measurements of atmospheric temperature profiles using the RASS. The original system was developed at Stanford University, Center for Radar Astronomy, in 1972 (Ref. 10). The basic concept, as the name suggests, is the tracking of sound waves with radar. The compression and rarefaction of the air by the sound waves alters the reflectivity of the air slightly and this is sensed in the radar return. However, the changes are so slight that no significant return signal would be sensed without two effects. First, if the acoustic source and radar transmitter and receiver are collocated (a

monostatic configuration), reflections from the entire spherical sound waves return to the radar receiver. Second, and more importantly, if the wavelength of the acoustic wave is half that of the electromagnetic wave the repeated reinforcement of the reflections increases the signal to noise ratio. This is the so-called *Bragg condition*.

There have been many applications of RASS to the measurement of atmospheric temperature profiles. These are reviewed by Clifford et al. (Ref. 11). Peters et al. (Ref. 12) examined the effects on the system of wind interference. Adachi et al. (Ref. 13) studied the effect of acoustic and radar pulse lengths on the system's accuracy. This latter reference provides a good analytical treatment of the operation of RASS under ideal atmospheric conditions. In the temperature-sensing mode, a monochromatic acoustic pulse or pulses are beamed vertically. Then they are interrogated by a radar pulse. At certain altitudes the speed of sound is such that the Bragg condition is met and there is a strong return. Since this return, for a given acoustic frequency, depends on the acoustic wavelength, which is a function of the speed of sound, the sound speed at that height is known. (The height being determined by the relative transmission and reception times.) A simple relationship between sound speed and local temperature is given by

$$S = 20.05\sqrt{T_v}, T_v = T(1 + 0.61q)$$

where S is the sound speed in m/s and T is the sensible temperature in K, q is the specific humidity, and T_v is the virtual temperature. Corrections must be made for other atmospheric conditions, such as vertical winds as these change the apparent speed of sound and makes the estimate of temperature inaccurate.

It is the influence of the (localized) vertical wind that makes RASS suitable for velocity sensing and, hence, its potential for wake vortex detection. In this case it is the local velocity that alters the apparent local speed of sound and the wavelength. Though this effect is obviously applicable to velocity fields that are relatively uniform, it can be used to detect the integrated effects of velocity and wavelength change in a localized region. It also has the potential, with suitable data analysis as discussed below, to determine the wake vortex velocity profile. William R. Rubin (Ref. 14) patented a RASS system for glide slope surveillance in 1992. The original concept relied on temperature changes associated with the pressure distribution in the wake vortex as the detection mechanism. Rubin (Ref. 15) describes a later embodiment of the device and Rubin et al. (Ref. 16) describe a test of the

sensor at New York's Kennedy International Airport. In this later version it is argued that the Doppler spectrum is uniquely related to the vortex velocity distribution and that the second moment of the measured Doppler spectrum, raised to the 2/3 power, is proportional to the strength (circulation) of the vortex. Though there are a number of simplifications in the analysis, the correlation between the measured vortex strength and the estimated strength based on aircraft weight was good. Figure 2.1 (from Ref. 17) shows a comparison of the observed and calculated vortex strengths. Also, the sensor gave consistently good vortex tracking results with a minimum of false alarms.

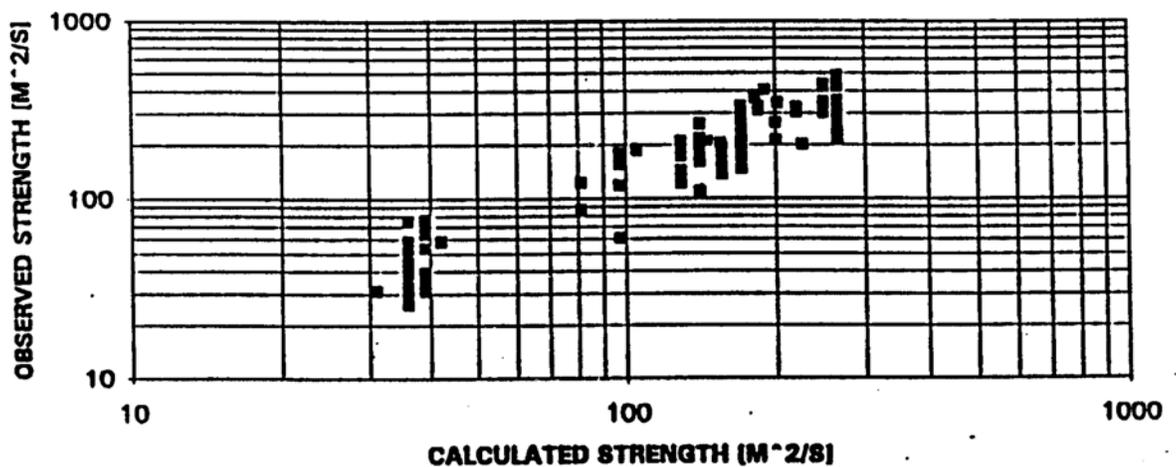


Figure 2.1: Comparison of Observed and Calculated Vortex Strengths (From Ref. 17)

Recently, Boluriaan and Morris (Refs. 18 and 19) have performed numerical simulations of a RASS for wake vortex detection. The calculations involved the simulation of both the electromagnetic and acoustic scattering problems. Their analysis showed that detailed information about the velocity distribution of the vortex as well as range information could be obtained. Figure 2.2 shows a calculated velocity distribution compared to the (model) Taylor vortex velocity profile. It should be noted these calculations assumed ideal conditions and the effectiveness of the proposed data analysis technique has yet to be field-tested.

The RASS has the following characteristics, not all featured in the other existing sensors (see Ref. 16):

- Vortex detection sensitivity
- All weather capability

- Vortex track capability
- Manageable cost
- Automatic operation
- Real-time measurements
- Meets airport operational constraints

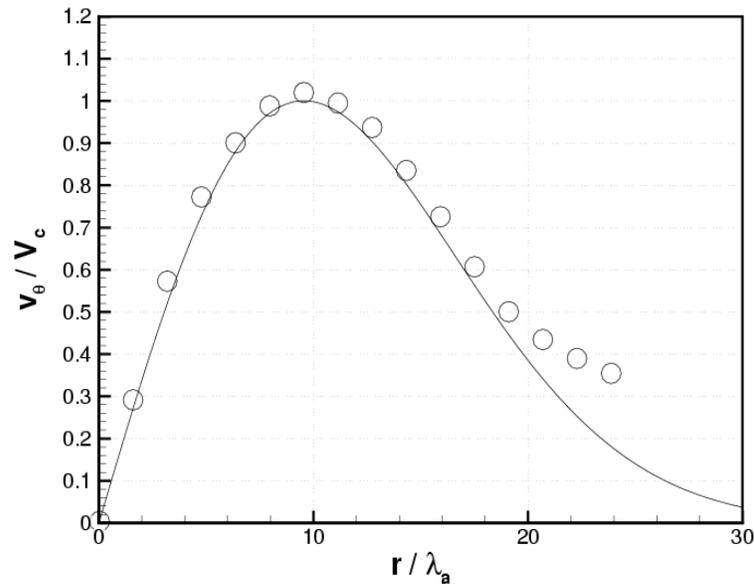


Figure 2.2: Comparison of Predicted and Taylor Vortex Radial Velocity Profile (from Ref. 18)

Conversely (see Ref. 20), the RASS has unknown reliability and is potentially environmentally unfriendly.

The validation of the relationship between the RASS system output and the velocity or vorticity distributions (or total circulation) of a vortex to date has been very elementary and needs to be improved considerably. The program described in the following pages would provide the type of measurement and verification required to produce adequate confidence in the instrument. In addition the envisioned system would be specifically designed for wake vortex detection and measurement, as opposed to being adapted from an instrument designed for atmospheric characterization.

3. Proposed Development Program

This section reports on a plan to develop a small scale RASS that would

- be used in the laboratory,
- be used in a series of flight tests with an inexpensive small aircraft (rental),
- be used to develop and test software for RASS signal analysis.

The physical size of the small scale RASS would be between 5 and 10 times smaller than the RASS previously used in wake vortex detection field tests (Ref. 17). The operating frequency of the radar (and the acoustic driver) would be approximately 10 times higher than the previous field test system. Hence the ratios of wavelengths to driver and receiver sizes are maintained in the same proportion between laboratory and full size field test systems. The power to be used in the small-scale systems will also be decreased according to appropriate scaling laws. These are requirements for proper model scaling if the model results are to be used in design modifications to the full-scale systems. More discussion of this modeling issue is presented in this section on RASS development, as well as in the following section on small-scale experiments.

3.1. Instrument Development

3.1.1. Hardware

The principal objective regarding hardware development is the design, construction, and evaluation of a sub-scale RASS test-bed that can be used in a variety of environments.

This test-bed will be used

- to develop and test software for RASS signal analysis
- to make laboratory-scale measurements under controlled conditions
- to perform field measurements for the evaluation of processing algorithms, using a small aircraft at reduced ranges appropriate to the scaling to full size.

In order to meet these diverse requirements, the hardware test-bed will be designed as a set of modules. There are three principal systems in a RASS: a radar transmitter, an acoustic transmitter, and a radar receiver. In the radar transmitter, there are five major components: a waveform generator; a modulator; a frequency translator to convert from the modulated intermediate frequency (IF) to the transmitted radar frequency (RF); a power amplifier; and an antenna. There are five complementary components for the radar receiver: an antenna; a low-noise RF amplifier; a frequency translator to convert the received RF signal to the intermediate frequency; a demodulator; and a detector/processor for the Doppler-shifted echo (see Fig. 3.1).

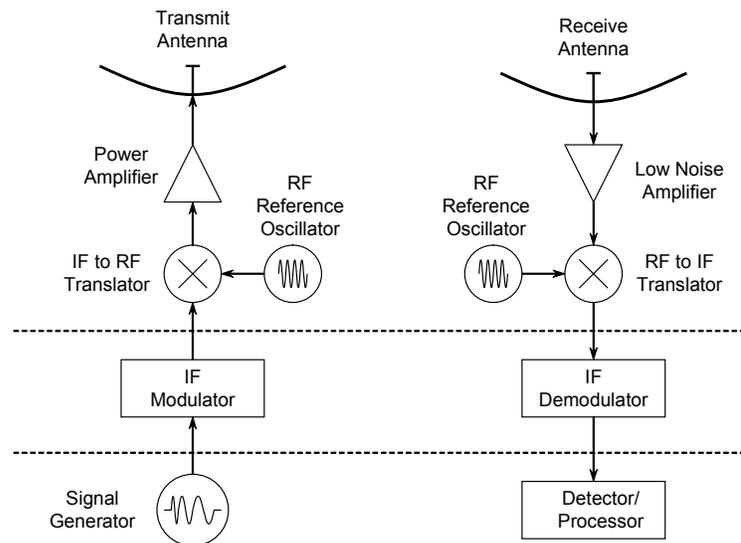


Figure 3.1. Radar transmit (left) and receive (right) systems. The dashed lines represent standardized interfaces to permit module interchange. The components in between the dashed lines are common to all configurations.

The acoustic transmitter consists of three major components: a signal generator, a power amplifier, and an acoustic transducer array (see Fig. 3.2).

This system design is proprietary to Penn State University.

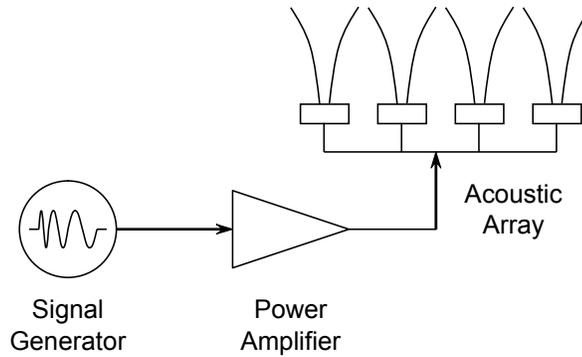


Figure 3.2. Acoustic transmit components for RASS. The signal generator and power amplifier are common to all configurations. The acoustic array would be modified to change the operating frequency.

For many of these components, commercial off-the-shelf equipment with little or no modification can be used. For example, the frequency translation from IF to RF and from RF to IF will be performed with off-the-shelf modules. The RF power amplifier and the RF low-noise amplifier are also off-the-shelf products as is the RF antenna. The modulation and demodulation of the intermediate frequency RF signal could be performed with a commercial module; however, the Applied Research Laboratory at Penn State has already developed a modulation/demodulation module that has more flexibility in selecting bandwidth and filtering options, so this existing in-house product will be used.

The development will proceed through several stages to retain maximum flexibility and also to evaluate performance as early in the development cycle as possible. The development of pulse types and subsequent signal processing is a large part of this project but simple pulse types generated by a commercial digital function synthesizer and a simple detection scheme can be used to perform the initial evaluation of the RASS test-bed. Consequently, the hardware development can proceed in parallel with the signal processing development and problems with the hardware can be identified and corrected early in the project evolution.

Next, an outline of the architecture for the proposed RASS test-bed is given.

Separate RF transmit and RF receive systems

The use of separate transmit and receive systems for the test-bed eliminates the blanking interval and circuit complexity associated with transmit/receive switching. For

experiments that require measurements at short distances from the antenna, switching delays and switching transients are unacceptable. Transmit/receive “circulators” are used in some systems but their design is more demanding and they still do not provide the same degree of isolation as separate transmit and receive systems. Furthermore, using separate transmit and receive systems permits bi-static operation: positioning the transmitter and the receiver at different locations. Bi-static operation allows additional design flexibility for better area coverage in a wake detection system.

Waveform generation and detection as a plug-in to RF system

Much of this proposed development effort will focus on waveform generation and optimal detection of returns from wake vortices. By designing the hardware system so that the details of transmission and reception are separate from the details of signal generation, detection, and processing, hardware and software development can proceed in parallel.

The radar modulation and demodulation modules will be designed to accept a variety of waveforms including continuous sinusoidal (CW) waveforms, pulsed CW waveforms, and frequency modulated (FM) waveforms. The acoustic modulation module will be designed to accept the same variety of waveforms.

Multiple operating frequencies with the same core system

The choice of operating frequency for a RASS depends primarily on the desired spatial and velocity resolution and the intended maximum range. Since the acoustic frequency and the RF frequency are linked by the Bragg condition, the propagation of both must be considered in the design.

The maximum range of a meteorological RASS (900 MHz RF; 2 kHz acoustic) is normally limited to a few kilometers by winds aloft. Horizontal winds eventually displace the acoustic Bragg pulse far enough so that it is out of the RF antenna’s beam. This range is more than adequate for a wake-vortex RASS; however, the spatial resolution of a 900-MHz system may be insufficient for reliable vortex detection in a wide range of meteorological conditions.

Spatial resolution can be increased by increasing the system frequency. However, if the RF frequency is too high, then absorption in fog, rain, or snow may limit performance in

those conditions. For one-way propagation distances of one or two kilometers, RF frequencies below the water-vapor absorption peak (near 25 GHz) should be usable under most conditions. Of more importance for RASS performance is the absorption of the acoustic signal. The approximate association between RF frequencies (for which commercial modules are readily available) and acoustic frequencies for direct Bragg backscatter is shown in Table 3.1 along with the acoustic absorption. In this table, the acoustic absorption is expressed as the distance traveled by the acoustic pulse for a 20 dB drop in level (a factor of ten decrease in amplitude) from absorption alone. Acoustic absorption is particularly sensitive to humidity so two values are included for each frequency. The first value is for typical average humidity in the atmospheric boundary layer; the second value is for the maximum loss. (At each frequency, the absorption loss peaks at a specific relative humidity. The peak-loss humidity ranges from 5% at 2 kHz to 30% at 20 kHz.)

Table 3.1. Acoustic absorption distances for RASS operating frequencies.			
Radar Frequency	Acoustic Frequency	m/(20 dB)^a	m/(20 dB)^b
1 GHz	2 kHz	2800	500
2.4 GHz	5 kHz	1100	140
5 GHz	10 kHz	300	75
10 GHz	20 kHz	80	40
^a meters traveled for 20 dB acoustic absorption for typical humidity			
^b meters traveled for 20 dB acoustic absorption for worst-case humidity			

This table can be used as a high-level guide for specification of a wake-vortex detection system. In the overall signal budget for a RASS, a 20 dB loss in acoustic signal level from absorption¹ would be acceptable even for a conservative design. The routine operation of the standard meteorological RASS (900 MHz or about 1 GHz RF and 2 kHz acoustic) to several kilometers altitude supports this view. The operational altitude requirement for a wake-vortex system is considerably less so the absorption losses in a 2.4 GHz system (but probably not a 5 GHz or higher frequency system) may be acceptable for full-scale operation. The 2.4 GHz system would have considerably better spatial resolution than the meteorological RASS for the same installation size and the acoustic frequency would be displaced from the peak in human hearing, which is about 2 kHz, making community annoyance less of an issue.

¹ Of course, this absorption loss is in addition to the transmission loss from spreading.

For field evaluation of design concepts with smaller aircraft (smaller, weaker vortices), a 5 or 10 GHz system would provide better resolution with the 10 GHz (“X-band”) system having sufficient spatial resolution for measurements of laboratory vortex generators. Commercial hardware is also available for 24 GHz (“K-band”) but at a much higher cost for the required power and a 24 GHz system would be useful only for laboratory measurements.

Modular construction

Insofar as is possible, off-the-shelf commercial modules or modules already developed and tested for other programs will be used in this construction. The intermediate frequency and modulation/demodulation functions will be performed using a module previously developed in-house. The output of this intermediate frequency module is matched to the commercial radar-frequency modules. In this way, the radar frequency of the RASS can be changed independent of the signal processing and modulation/demodulation functions and a system developed for laboratory- and small-scale experiments can be converted for full-scale demonstrations. Suitable RF modules are available from 900 MHz to 10 GHz.

If the radar frequency is changed, the acoustic frequency must be changed also. Because broadband acoustic power amplifiers are inexpensive and readily available, the same signal generation and amplification modules can be used for any of the required acoustic frequencies. The physical configuration of the acoustic array would be changed and different acoustic drivers would be used for 20 kHz than for the lower frequencies.

Expected signal levels

The feasibility of a RASS can be examined initially by considering the expected signal levels. The success of an active system depends on a sufficient ratio of echo level to noise level in the detection processor. By tracking signal and noise levels through the proposed system, the echo-to-noise level can be estimated but successful detection depends on details of the detection process and that process is one of the subjects of this investigation. However, the radar and acoustic levels can be compared to those of a meteorological RASS. A comparable echo-to-noise level would indicate a high probability of reliable operation for

the proposed system. For this comparison, the noise floor of both systems will be assumed to be the same.

For example, consider a 10 GHz system designed for laboratory measurement of artificially generated vortices under controlled conditions. For such a system, it would be desirable to resolve 0.2 m/s in wind speed, 1 m spatially in “altitude” (in the direction of propagation of the radar signal), and 0.2 m spatially perpendicular to the beam². The length of the Bragg interaction region controls the resolution in the altitude direction, while the resolution in the cross-beam direction is controlled by the beam patterns of the radar and acoustic systems. A comparison between this system and a 900 MHz meteorological RASS (see Refs. 21, 22 and 23) is given in Table 3.2. Also shown for completeness is 2.4 GHz frequency system. This system could also be fabricated from off-the-shelf components. The ability to consider these different systems will allow the optimization of the RASS for wake vortex detection. This new system would not be constrained to have the same operating conditions as a system originally developed for atmospheric sounding.

Table 3.2. Comparison of radar and acoustic signal levels between a 900 MHz RASS measuring at 1 km altitude, a low-power 2.4 GHz demonstration RASS measuring at 250 m, and a 10 GHz small-scale RASS measuring at 10 m. These are not maximum operating altitudes.

Parameter	900 MHz RASS	2.4 GHz RASS	10 GHz RASS
RF frequency	0.9 GHz	2.4 GHz	10 GHz
RF wavelength	0.33 m	0.125 m	0.030 m
RF intensity	800 mW/m ² at 1 km	60 mW/m ² at 250 m	1500 mW/m ² at 10 m
Acoustic frequency	2 kHz	5.5 kHz	22 kHz
Acoustic wavelength	0.17 m	0.062 m	0.015 m
Acoustic intensity	0.25 mW/m ² at 1 km	0.25 mW/m ² at 250 m	38 mW/m ² at 10 m
Acoustic pressure	0.3 Pa at 1 km	0.3 Pa at 250 m	4 Pa at 10 m
Length of Bragg pulse	600 λ (100 m)	400 λ (25 m)	70 λ (1 m)
RF return-path loss	60 dB	48 dB	20 dB

Compared to the meteorological system, the laboratory system with a 2-watt transmitter has the capability to produce almost twice the RF intensity at the test point and about 100 times the acoustic intensity. The length of the Bragg pulse (the acoustically produced scattering region) controls the achievable spatial resolution along the beam direction. A shorter pulse improves spatial resolution but at the expense of scattering strength. The amplitude of the scattered RF pulse (the radar “echo”) is proportional to the

² These are “raw” resolutions prior to any signal processing or image enhancement.

number of *wavelengths* in the acoustic Bragg pulse. So a higher operating frequency produces improved resolution even if the same number of wavelengths is used in the Bragg pulse. The 10 GHz system design uses a one one-hundredth the physical length of the 900 MHz Bragg pulse but the amplitude of the scattered RF pulse should only be about one-tenth that of the meteorological RASS.

A higher acoustic intensity compensates for the weaker scattering from the shorter Bragg pulse; however, the RF level at the receiving antenna will still be much larger in the laboratory system because the return-path loss is much lower than in the meteorological system. This comparison indicates that the laboratory system should produce echoes of comparable detectability to a meteorological RASS out to distances (or altitudes) of several tens of meters. Lower frequency (2.4 or 5 GHz) operation of the test-bed would yield longer ranges for two reasons: the acoustic absorption losses would be lower and higher power RF transmitters are readily available.

Similar comparisons can be done for other operating frequencies. In the comparison above, the acoustic levels are estimated based on measurements of real acoustic drivers while the radar levels are estimated from the RF amplifier output power and a conservative estimate (25%) for antenna efficiency. The same receiver noise performance³ is assumed for both the developmental RASS and the meteorological RASS.

First stage development

The hardware development will take place in stages and the development is planned so that problems can be identified and corrected as early as possible. The first stage will consist of two phases: (1) assembly of off-the-shelf components to ensure that adequate echo levels can be obtained from simple Bragg interaction, and (2) minor modification of the RF sections to synchronize the reference frequencies for transmit and receive. The plan is to develop the 10 GHz system for laboratory and small-scale controlled experiments but any of the other candidate frequencies can be chosen without significant alteration of the development plan.

³ With recent advances in low-noise RF preamplifiers, it is more likely that the laboratory system will have better noise performance than existing meteorological systems.

An acoustic array will be built using high-frequency horn transducers and the directivity and the acoustic level at the maximum range will be measured. The RF transmitter module driven by the laboratory intermediate frequency module will be used without modification to measure the RF intensity at the maximum range. The RF receiver module feeding the laboratory intermediate frequency demodulator will be used to measure the noise floor of the receiving system.

The critical test for the first stage system is the assessment of the echo level from an acoustic Bragg scattering patch. For this test, the radar transmitter and receiver will be run continuously and the acoustic system will be pulsed. When the acoustic pulse is not present, the receiver output will provide a measure of the “cross-talk” between the RF transmitter and receiver. This can be direct electromagnetic coupling, leakage from the antenna patterns, or scattering from nearby reflectors⁴. This cross-talk will appear at the same RF frequency as the transmitted RF signal. When the acoustic pulse is present, a signal should appear in the received spectrum that is lower in frequency than the cross-talk return and the down shift should be equivalent to the Doppler shift associated with the acoustic pulse’s speed of propagation. The intent in this preliminary measurement is not to measure wind speed; the intent is to ensure that the system can detect clearly the Bragg return and to measure the amplitude of both the Bragg return and the cross-talk “return.”

Once detection of a Doppler-shifted return from the acoustic Bragg pulse has been confirmed, the RF sections of the transmit and receive systems will be modified slightly. The Doppler shift that results from the speed of sound is fairly large (20 to 25 kHz for the 10 GHz system but local wind or vortex velocities are much less than the speed of sound so the RASS must be capable of measuring small differences in frequency⁵ relative to the RF “carrier.” For separate transmit and receive systems, resolving localized wind speed is only practical if both systems are linked to a common reference oscillator. To perform this modification, the separate reference oscillators in the transmit and receive systems (compare to Fig. 3.1) will be replaced by a common external reference oscillator. Even with drift in this reference oscillator, Doppler shifts can always be measured relative to the reference since both the transmitter and the receiver will drift the same amount. Since the spatial

⁴ For a pulsed radar system, the spurious signals from antenna sidelobe leakage and unintended reflections are sometimes called “clutter.”

⁵ A 1 m/s wind would produce a Doppler shift of 7 parts per billion in the radar echo for direct backscatter.

sampling volume of the 10 GHz system is small, the developmental RASS will be evaluated outdoors by orienting the beams horizontally and using an anemometer (and temperature sensors) to measure the true wind speed.

Second stage development

The principal objectives of the second stage development are: (1) to establish the spatial and velocity resolutions achievable with the system and (2) to determine the received signal strength as a function of the characteristics of the transmitted waveforms.

In the first development stage, the RF reference oscillator signals were synchronized. In the second stage, a common oscillator will also be used for the intermediate-frequency stages so that the transmit and receive systems are synchronized at all stages. This will allow optimizing the frequency resolution of the Doppler-shifted echo, which, in turn, optimizes the velocity resolution. The beam patterns of the radar antennas and the acoustic array will be tuned for best spatial resolution.

Using digital function synthesizers for waveform generation of both the radar and the acoustic signals, the performance of the testbed system will be evaluated using laboratory-generated vortices (see Section 3.2). Of particular importance is measuring the dependence of echo signal strength (and signal-to-noise ratio) on pulse type and pulse length.

Third stage development

The second development stage essentially completes the hardware development. The third stage of development involves integration of the digital signal generation and digital signal processing into the RASS hardware. The development of the digital signal generation, detection, and processing software is discussed in the next section.

3.1.2. Software

The proposed signal processing analysis will be based on that developed by Boluriaan and Morris (Refs. 18 and 19). During the first stage of the instrument development, the analysis will be performed using an off-line personal computer. In the later stages, a real-time data analysis system will be developed as part of the instrument. This section gives a brief description of the expected signals and the data analysis methodology.

Figure 3.3 shows a typical backscattered electromagnetic signal. This time series data carries vortex velocity information in the direction of the incident radar beam. In order to extract this information, a series of signal post-processing procedures needs to be performed.

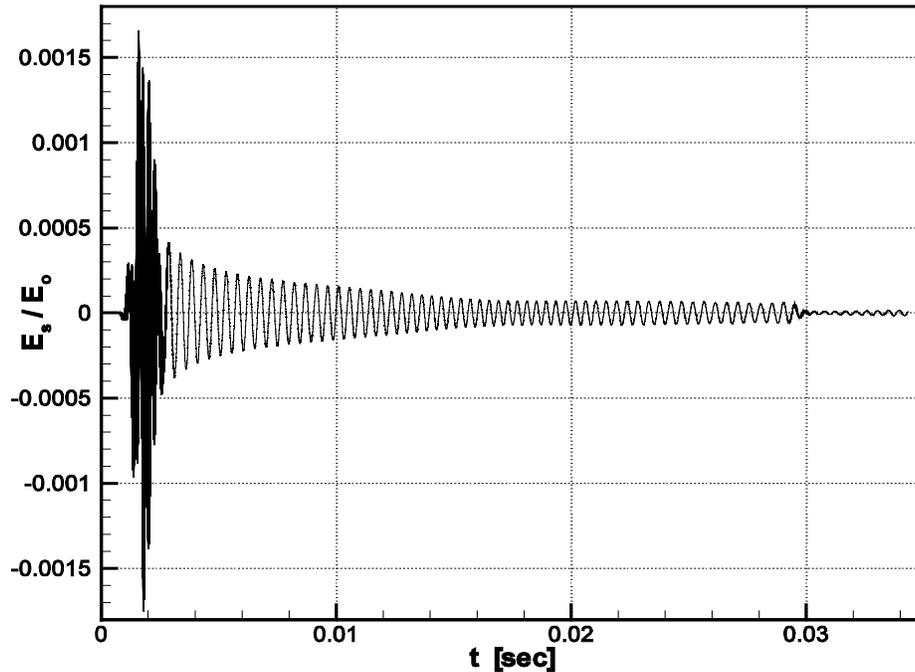


Figure 3.3: A typical backscattered electromagnetic signal from a wake vortex.

First, the signal is divided into a number of slices, and the power spectrum of each slice is calculated. The Doppler shift of the power spectrum of each slice with respect to the incident reference signal gives the vortex velocity that corresponds to the location from which this particular slice came, that is, the sampled volume. It is then necessary to relate the signal arrival time to the location of the sampled volume:

$$\text{Arrival Time} = t_o + t_{AC} + t_{EM}$$

where t_o is the acoustic pulse departure time, t_{AC} is the time required for the acoustic pulse to reach to the sampled volume, and t_{EM} is the time required for the electromagnetic scattered signal to return to the receiver from the sampled volume. t_o is known and t_{EM} can be easily calculated given the fact that the electromagnetic wave speed is constant. It is also possible to neglect t_{EM} as it is several order of magnitude smaller than t_{AC} . The calculation of t_{AC} ,

however, is not straightforward since it depends on the local sound speed in the environment and the convection velocity of the vortex, and the latter is unknown beforehand. In order to overcome this difficulty, t_{AC} is determined first assuming no mean flow, and then, based on the estimated vortex velocity, t_{AC} is adjusted. This process could be repeated any number of times. However, any adjustment beyond the first correction is found to be very small.

The resolution of the calculated vortex velocity field depends on the size of the sampled volume, which in turn it depends on the radar beam width and the time duration of each time slice. A narrower radar beam width or a shorter time slice results in a smaller sampled volume and a better resolution of the velocity field. However, there are physical and mathematical constraints that limit this resolution. The radar beam width is limited by equipment availability. A shorter time slice means fewer samples in each time slice and a poor frequency resolution of the power spectrum.

It should be mentioned that the velocity field that is obtained by this method represents the vortex velocity component in the transmitter direction. An Abel transform can be used to convert this velocity component and obtain the radial variation of the vortex velocity field. Boluriaan and Morris (Refs. 18 and 19) describe this in more detail.

The post-processing analysis described here has to be performed in real time in a deployable RASS system. This means that the backscattered electromagnetic signal should be streamed continuously to the post-processing box and the calculated wake vortex velocity field has to be reported in real time. The post-processing calculations can be computationally intensive since they involve numerous power spectrum calculations. As a result, it may not be able to keep up with the inflow data stream particularly if a fine frequency resolution is required. The solution lies in use of a parallel Digital Signal Processing (DSP) card as sketched in Fig. 3.4. The Fourier transform algorithm, needed to obtain the power spectra, is built into the DSP card hardware. As a result, the calculations can be done significantly faster than a software-based algorithm. Furthermore, the parallel DSP card, as the name suggests, has the ability to perform multiple tasks in parallel and provide the wake vortex velocity field in real time.

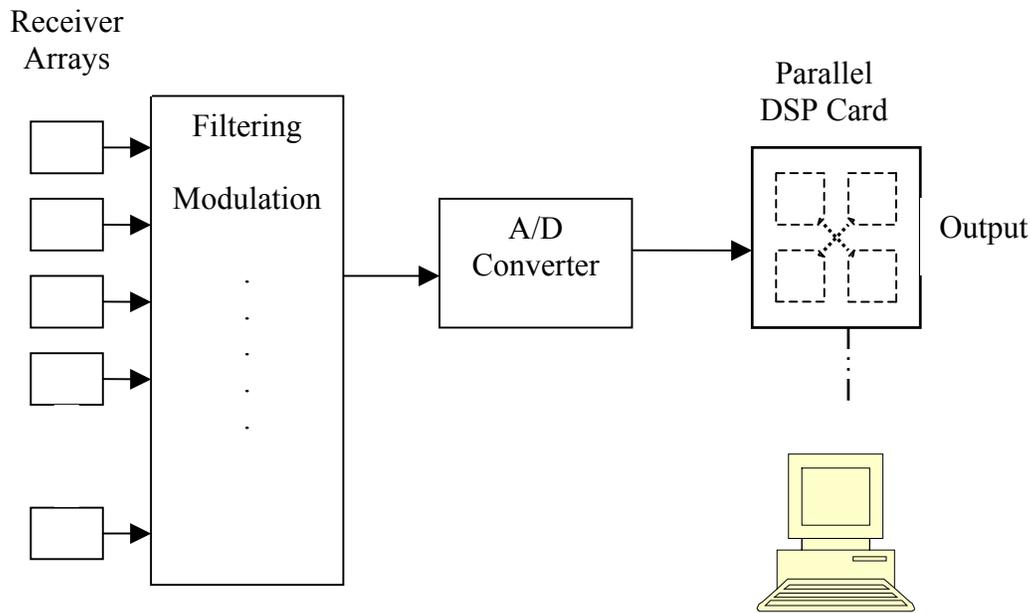


Figure 3.4: A schematic diagram of a parallel DSP card. In this particular sketch the DSP card can perform four tasks in parallel.

3.2. Laboratory and Small-Scale Flight Experiments

This section reports on a plan to develop the laboratory and small-scale flight tests that would be used to test and further develop the small scale RASS. These experiments will first produce a comprehensive study of the details of the measurement of a vortex produced in the laboratory. This vortex will be representative of one of a pair of wake vortices produced by an aircraft wing. Secondly, the same system will be taken to the University Park airport for measurements of wakes of small aircraft. The scale of the RASS will be (approximately) in the same proportion to the core sizes of the vortices as well as the range of the system from the aircraft wakes. It is anticipated that the laboratory system will be used in the development of a RASS that is optimally suited for the measurement of vortex wakes. RASS systems used to date have been adapted to vortex wake measurements from the primary application of atmospheric profiling.

Laboratory Experiments

As described above, the laboratory RASS will be designed to possess all of the essential ingredients of the previously used “full-scale” RASS. However, as with virtually any model system, it will be much easier (and economical) to change important characteristics of the system that could lead to a more optimized instrument. Examples of these characteristics include (but are not limited to): the acoustic beam directionality and capability of operation in the burst mode; the strength of the radar return in the absence of a vortex in the interrogation field; how this radar return varies with the transmitting radar beam pattern; and its associated range gating system.

In the laboratory experiments the position of the vortex will be known with reasonable precision in advance of the data acquisition. The vortex will be established and the facility will be operated over an extended set-up time prior to data acquisition. To a high degree of engineering certainty, the vortex properties will remain constant while the RASS operational parameters are modified to produce improved measurement fidelity. The system concepts can then be applied to actual field test situations in which the instrument is measuring a time-evolving event.

In designing the vortex generator it should be kept in mind that the dominant features of the far wake of an aircraft are a pair of vortices. Also, each vortex has a wake profile within its core. This is sketched on the left hand side of Fig. 3.5. The wake profile is the case when the frame of reference is riding on the aircraft. When the reference frame is on the ground, the core of the vortex is actually a jet. This is shown in the right side of Figure 3.5. This is the rationale for designing an experiment that will include a vortex jet as the primary facility for the new RASS qualification experiments.

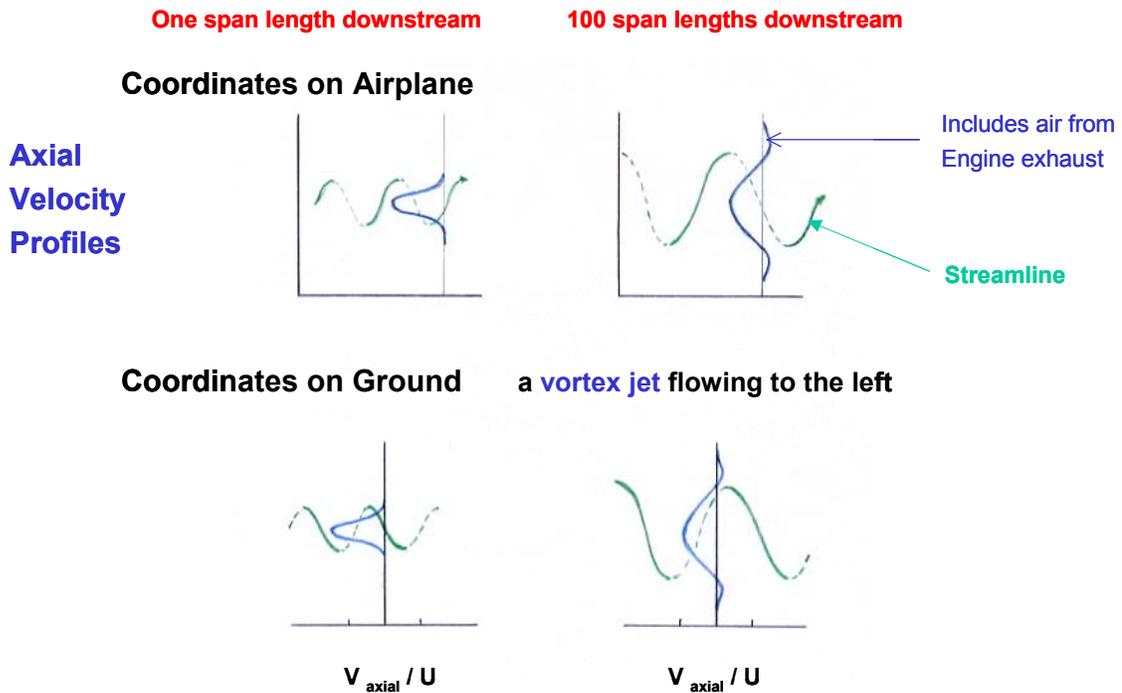


Figure 3.5: Typical velocity profiles for wake vortices measured from moving and ground-based coordinate frames. Note that an axial velocity deficit in airplane coordinates gives an axial jet in ground-based coordinates.

The vortex jet is generated by the facility shown schematically in Figure 3.6, and in the photograph of Figure 3.7. The “settling chamber” of the nozzle has a 16:1 contraction ratio, by area. There are two inlets to the nozzle, one in the axial direction on the centerline, and the second entering tangentially to impart the swirl to the jet. By changing the ratio of the flows from the two inlets, the ratio of jet axial velocity to peak tangential velocity can be controlled. This ratio is a measure of the age of the wake vortex that is being simulated. The radius of the jet core in the region of measurements will be approximately 1/20 of size of the core of a (far) wake vortex behind a large transport aircraft. This scale is not exactly in the same proportion as is the physical size of the RASS, nor the inverse of the ratio of operating frequencies of the system. In fact this size ratio will put more stringent requirements on the resolution and fidelity of the RASS and is therefore not believed to be a serious problem.

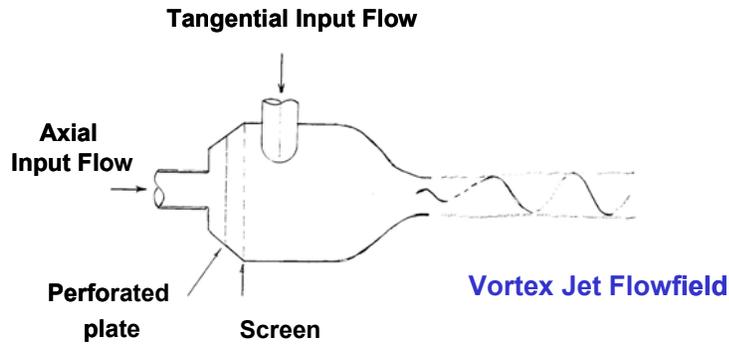


Figure 3.6 Vortex jet schematic



Tangential Input Flow

Figure 3.7 Photograph of nozzle

The laboratory experiments introduce a capability not currently available to those attempting to improve the capability of the current full size RASS. As described above a vortex can be established in the laboratory that is stationary in time over extended periods of time on any experimental day. The essentially stationary vortex in the laboratory facilitates flowfield measurements with a precision that is not possible in full-scale field tests.

A necessary component of the laboratory facility is the “flow through” anechoic chamber (shown in Figure 3.8). The quiet powered exhaust in this facility draws in the “end” of the vortex so that remnants of it do not recirculate and “contaminate” the primary vortex.

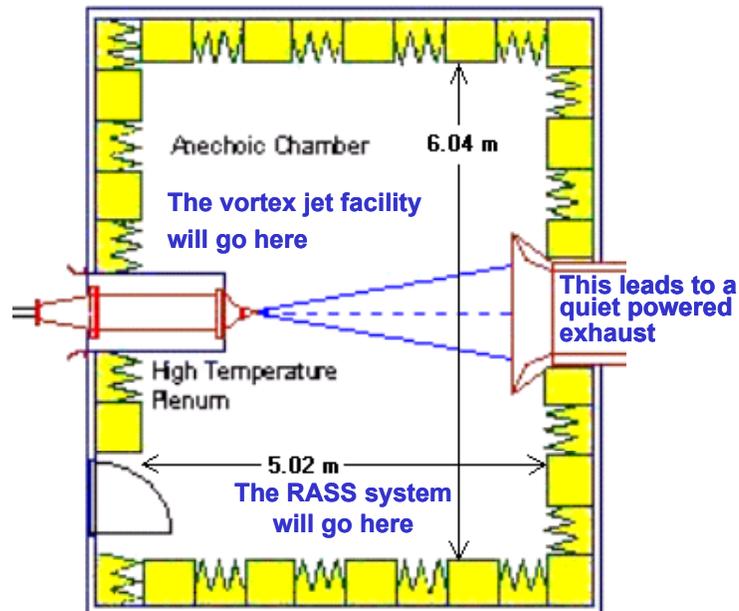


Fig 3.8 The anechoic chamber test facility

This facility has the added advantages of absorbing the acoustic beam component of the RASS so that wall reflections will be negligible. (This schematic shows the high temperature plenum that is used in jet noise studies. This will be removed and replaced with the vortex jet set-up for the proposed experiments.)

The velocity field within the RASS measurement region of the vortex jet will be measured with the precision common to the laboratory experiments. These measurements will be compared to the major vortex wake measurements that exist today. (For example, refs 24, 25 and 26.) The vortex measurements will be performed with a combination of: particle image velocimetry the PIV, a five-hole pitot probe for mean flow properties, and hot-wire anemometry predominantly for turbulence properties. (The PIV will determine mean velocities as well as limited turbulence properties).

A sample of the output of a PIV system set up to measure the components of velocity in a plane perpendicular to the vortex jet axial flow direction is shown in Figure 3.9. The data on the left hand side of this figure shows a validated single realization vector map of the swirl components of velocity. The data on the right hand side of the figure shows an ensemble average vector map. The difference between the two figures represents a single time measurement of the velocity fluctuations (turbulence) in this cross-stream plane.

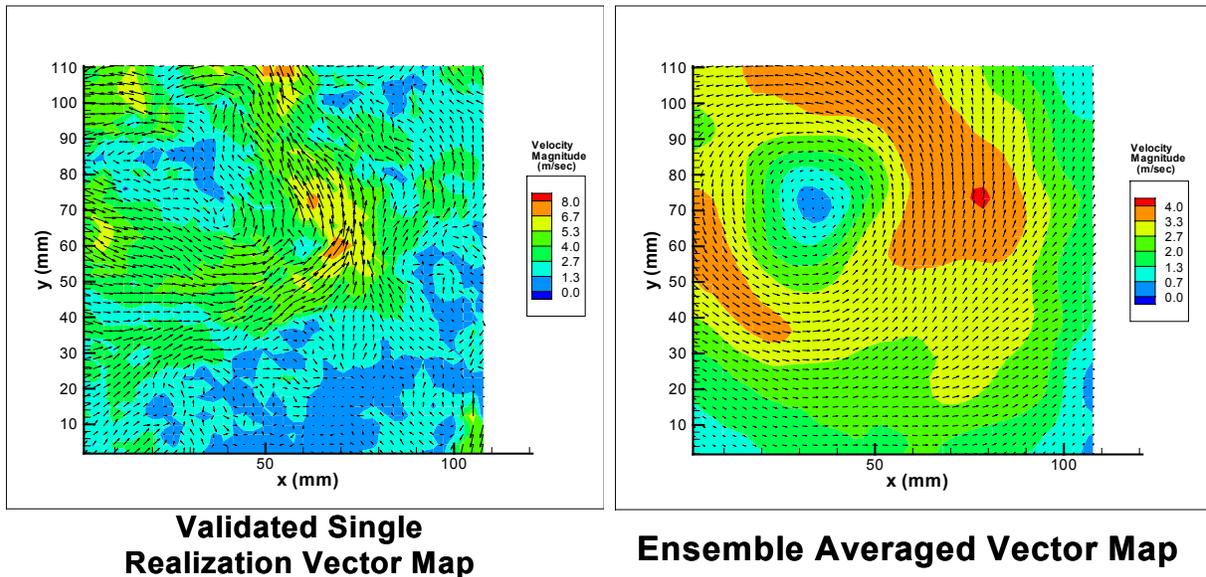


Fig. 3.9 Examples of data measured with the PIV system in the vortex jet.

The major components of the PIV system used to make the measurements shown are depicted in Figures 3.10 and 3.11. Figure 3.10 is a schematic diagram of the optical components of the PIV while Figure 3.11 is a block diagram of all major components of the system. Because the 2D PIV system is only capable of measuring components of the velocity field in a plane it cannot provide the information we require for a “full characterization” of the vortex jet. We anticipate using our 3D, “stereoscopic” PIV system for such a complete set of measurements. This system has been under development and extensive evaluation for some time in our laboratory (Ref. 27).

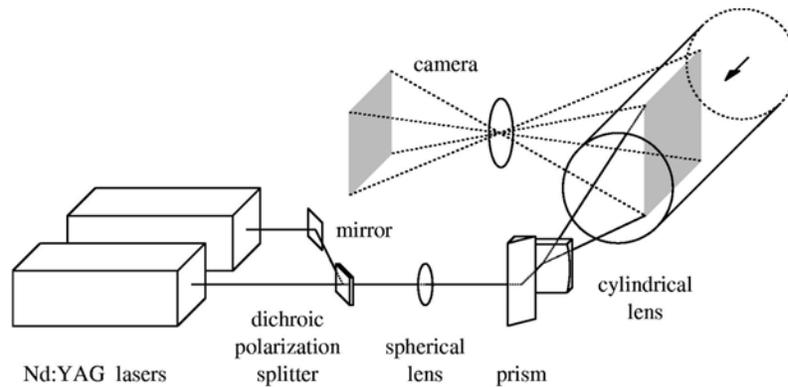


Fig. 3.10 Schematic of optical components of two dimensional PIV system

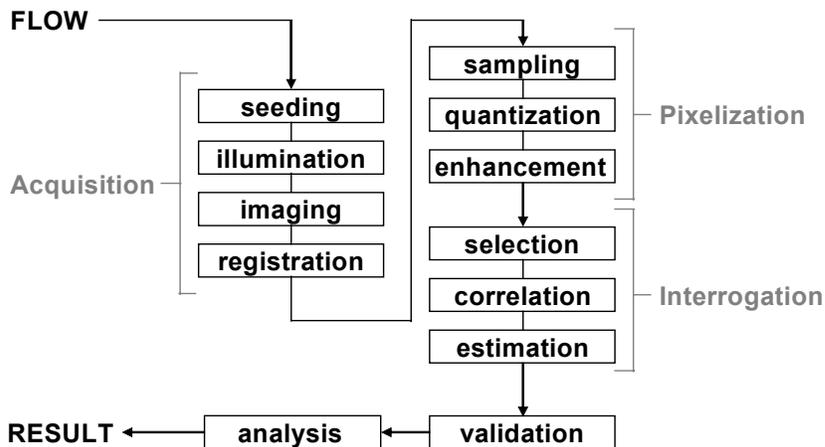


Fig. 3.11 Block diagram of the major components of a PIV measurement system

Figure 3.12 shows a schematic diagram of the essential ingredients of the 3D PIV optical system. (Note that the system that establishes the planar light sheet (shown in Figure 3.10) is the same for both 2D and 3D PIV systems.

To ensure the accuracy of the PIV measurements a limited number of measurements will be made with the five hole Pitot probe and the hot-wire anemometer. Both of these measurement systems are well established in the aeronautical research community and do not need to be described here. The systems we will use for these measurements are summarized in references 28 and 29.

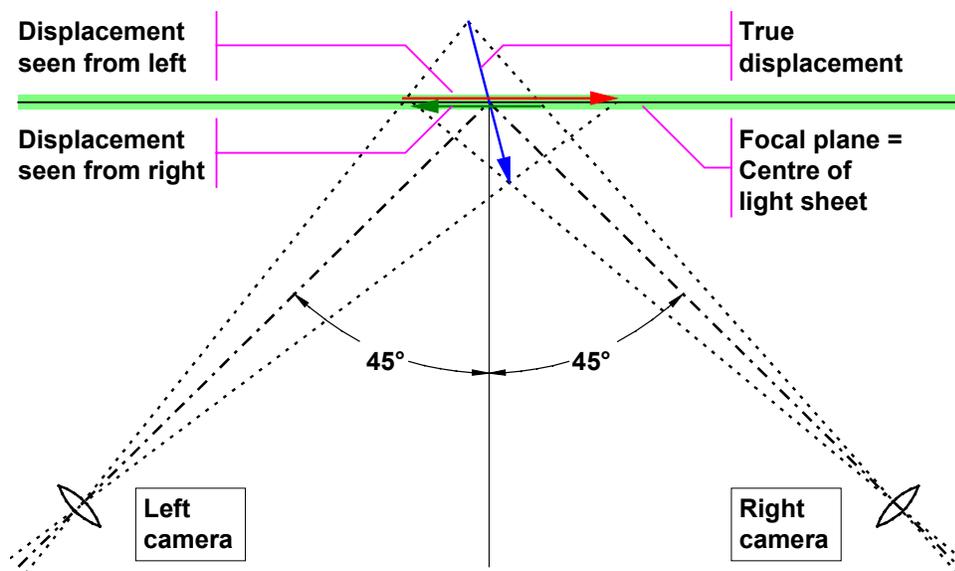


Fig. 3.12 Schematic of receiving optics of a 3-D PIV system.

In summary, the laboratory experiments will provide a “test-bed” that will be used to make both RASS and flowfield measurements to facilitate design improvements to the RASS. It is anticipated that numerous modifications to the “original” design will be required to produce a near optimum design with significantly improved performance.

Further evidence of the validity of the design assumptions will result from extension of the laboratory experiments to a small-scale field test.

3.2.1 Small Scale field tests

The plan includes a series of inexpensive small-scale field tests to evaluate the improved RASS in more realistic wake vortex experiments. The RASS developed in the laboratory will be moved to the University Park airport to a location under the final approach to the main runway. The distance from the RASS to the aircraft wakes will be considerably further than those used in the laboratory experiments. In addition the aircraft vortices (the core radius dimension) will be larger than in the laboratory experiments. We anticipate the ratio of sizes of the vortex cores, the range of the measurements and the RASS physical dimensions will all be very close to the inverse of the RASS operating frequencies. In this manner the scaling will be more precise leading to high confidence in our ability to transform the improved design to a full-scale system.

The small-scale field tests will focus on characterizing the wake vortices of a small general aviation aircraft as a function of the age of the wakes and some of the parameters of the aircraft (such as landing speed and aircraft gross weight and angle of attack). In addition, the environmental impact of the system such as the level of increase to community noise will be assessed. At the conclusion of these experiments we will be in a strong position to suggest performance parameters of future RASS instruments and potential for improvements in comparison to existing systems. These potentials will be quantified so that future cost benefit analyses will be greatly facilitated.

4. Conclusions

A brief review has been provided of existing instruments for wake vortex detection including the previous implementations of a RASS. As a result of this review, it is concluded that the basic features of a RASS have advantages over other commonly used wake vortex detection and measurement systems. Most important of these features are the good fidelity of the measurements and the potential for all weather operation. To realize the full potential of this remote sensing instrument, a plan for the development of a RASS designed specifically for wake vortex detection and measurement has been prepared. To keep costs to

a minimum, this program would start with the development an inexpensive laboratory-scale version of a RASS system. The new instrument would be developed in several stages, each allowing for a critical assessment of the instrument's potential and limitations. The instrument, in its initial stages of development, would be tested in a controlled laboratory environment. A jet vortex simulator, a prototype version of which has already been fabricated, would be interrogated by the RASS system. The details of the laboratory vortex would be measured using a Particle Image Velocimetry (PIV) system. In the early development stages, the scattered radar signal would be digitized and the signal post-processed to determine how extensively and accurately the RASS could measure properties of the wake vortex. If the initial tests prove to be successful, a real-time, digital signal processing system would be developed as a component of the RASS system. At each stage of the instrument development and testing, the implications of the scaling required for a full-scale instrument would be considered. It is concluded that a RASS system, developed for the specific application of wake vortex detection, could become part of a robust Aircraft Vortex Spacing System (AVOSS). This system, in turn, could contribute to Reduced Spacing Operations (RSO) in US airports and improvements in Terminal Area productivity (TAP).

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